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A Time-Division Multiplex Communication Network Featuring Decentralized Switching and Reduced Bandwidth

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0 Introduction

If a communication network level is without a switching center, but each station has a switching unit of its own, that network level is said to feature decentralized switching Communication networks of this type in which all stations have multiple access to the transmission capacity of a common transmission medium have been under discussion for some time [1]

Various proposals relying on the use of a branched network of two-path lines for transmission in opposite directions (branched or tree network) were first outlined in [2, 3] Of these the time-division multiplex system with information feedback described in [4] has the most favorable features Blocks of information do not have to be preceded by an address (time slot addressing, cf also Section 5) and the entire network operates without the need for such blocks to be buffered Circuit switching between any two stations demands however a doubling of the bit rate for the messages in each of the two directions of transmission

The proposal for a time-division multiplex network with a tree configuration as outlined below reduces the above bit rate requirement by about 50% A network with less than two nodes likewise operates without the need for buffering, while a network with $\iota \geqq 2$ nodes requires $\iota - 1$ buffers The following description will first treat a network with exactly one node and its mode of operation will be illustrated with reference to the telephone subscriber network level in order to allow comparison with [4] The application of such network configurations may possibly be restricted to a subscriber-related network level of concentrators

1 Network Configuration

The communication network consists of branches, each branch consisting of two paths for the two directions of transmission, a node with a branching unit, stations, a synchronizing generator and synchronizing reflex units (Figure 1) One end of each branch is connected to the node, while the other end is terminated with a synchronizing generator in the case

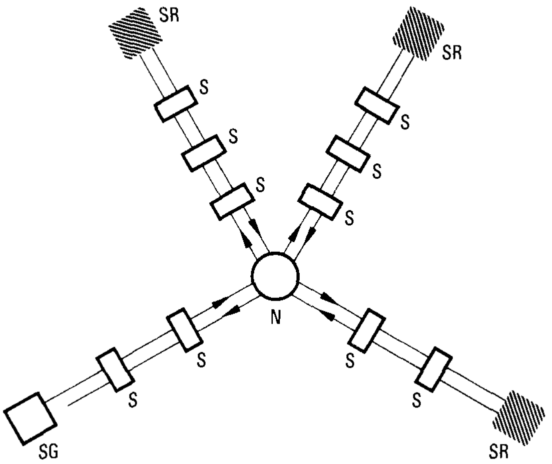

Figure 1 Network configuration SG Synchronizing generator SR Synchronizing reflex unit S Station N Node

of one branch and with a synchronizing reflex unit in the case of the remaining branches Any number of stations can be connected to any branch If there is only one branch, there will be no node and the network will constitute the special case of a linear network

2 Branching Unit

The branching unit of a network with z branches will consist of z or-gates with $z-1$ inputs each An outgoing path is used to transmit the result of the combination of those signals which arrive over the incoming paths of the other branches Figure 2 shows the circuit configuration of a branching unit for three branches

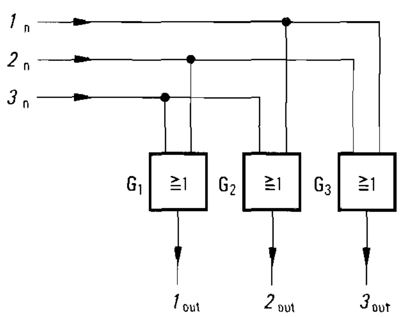

Figure 2 Branching unit for three branches 1_n 2_{in} 3_n are incoming paths 1_{out} 2_{ou} 3_{ou} are outgoing paths G_1 G_2 G_3 are or gates

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3 Frame and Time Slot Bit Sequence

The frame is subdivided into an even number of time slots (Figure 3) In a communication network featuring decentralized switching, the occupation of a time slot must be clearly recognizable It must further be clearly recognizable whether an occupied time slot contains usable information, a call signal to a station, or some other type of signaling information Additional conditions which need to be met with this network are treated in Section 7 All conditions are satisfied by using the following bit sequence

The first of the 18 bits of each time slot is the timing bit T, the second the signaling bit S and the remaining 16 bits U_1, , U_{16} are usable bits Using conventional PCM coding with 8 bits per sample, two samples are transmitted in common per time slot The synchronizing generator sets the timing bit T to 1 in even-numbered time slots and to 0 in odd-numbered time slots (Section 4)

Only when the signaling bit and all the usable bits are 0 will the time slot be unoccupied Otherwise it will be considered occupied The various types of information are characterized as follows

(a) If a station has to transmit usable information in the usable bit positions it will set the signaling bit to 1

(b) If a station has to transmit a call signal or other signaling information in the usable bit positions it will set the signaling bit to 0 The information in the usable bit positions is then defined at two specification bit positions within the group of usable bits For transmitting a call signal a calling station will set the two specification bits to 10 and for all other signaling codes to 01 The signaling bits and the two specification bits will be treated below in the sequence (signaling bit, first specification bit, second specification bit)

The first time slot contains the frame alignment signal For this time slot the synchronizing generator sets the signaling bit and the specification bits to 001 Since the remaining usable bit positions contain a code combination reserved for the frame alignment signal, the latter cannot be simulated by a signaling code The second time slot can be reserved for transmitting control information from the node to the synchronizing

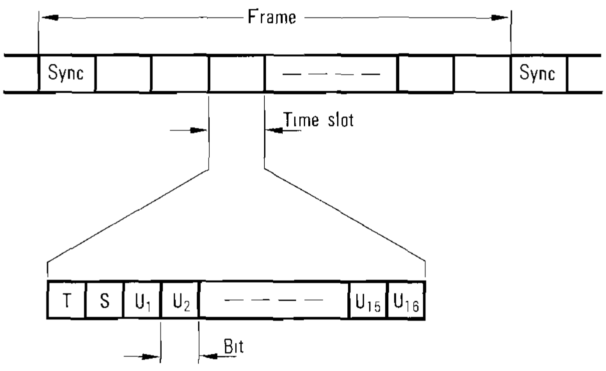

Figure 3 Frame and time slot bit sequence Sync Frame alignment signal T Timing bit S Signaling bit U_1 U_2 U_{16} Usable bits

reflex units The number of speech circuits must be chosen in correspondence with the traffic parameters of the stations and the grade of service specified for the network An additional time slot is required for each speech circuit These time slots will be referred to below as usable time slots

4 Synchronization of Network and Network Units

The synchronizing generator transmits the periodic synchronizing information, thereby establishing the timing for alignment of bits, frames and time slots within the network The branching unit at the node transfers the synchronizing information to the outgoing paths of the other branches so that it propagates throughout the network to all the synchronizing reflex units at the ends of the branches (Figure 4) These units

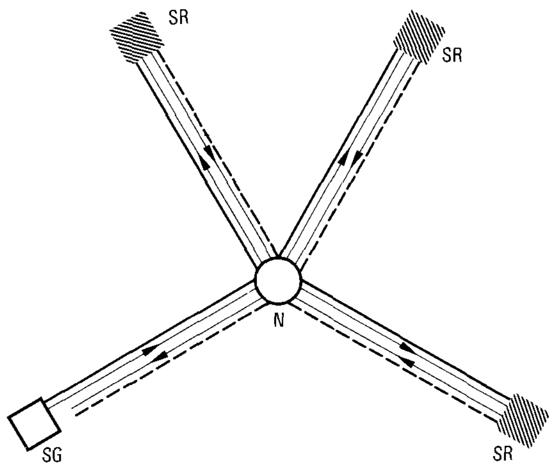

Figure 4 Network synchronization (stations not shown) SG Synchronizing generator SR Synchronizing reflex unit N Node —— Synchronizing information from SG -- Synchronizing information from SR

extract the synchronizing information from the incoming path and transfer it with a certain delay to the path leading to the node [4] This delay is determined by the node such that the propagation time of the synchronizing information from the node to a synchronizing reflex unit and back is an integral multiple of the duration of the TDM frame Thus all the TDM signals arriving over the incoming paths reach the node with frame coincidence A synchronizing reflex unit can be implemented as a generator operating in bit-synchronism with the synchronizing generator and transmitting the periodic synchronizing information with a controllable delay relative to the incoming frame alignment signal Thus no (frame) buffer is required for network synchronization Small variations in the signal propagation time of the transmission path can be equalized by small buffers at the node

If an or-gate combines a binary signal with one or more identical signals, the same signal will result Thus the branching unit will additionally transfer the synchronizing information to the path leading to the synchronizing generator and the synchronizing information already present in the other paths outgoing from the node will not be disturbed.

If all the available time slots are free, the alternating timing bit will cause a 1 to appear before or with the 36th bit of the described bit sequence. If all the available time slots are occupied, the alternating timing bit will cause a 0 to appear before or with the 36th bit in the case of the worst bit sequence, where 1 continuously appears as usable information in all time slots. These alternations allow the synchronization of the network units without elaborate effort. If two consecutive timing bits T_1, T_2 with 1 and 0 are provided for each time slot instead of the alternating timing bit T (Section 3) the synchronization of the network units can be further simplified at the cost of higher transmission speed.

5 Time Slot Pairing and Message Addressing

The two time slots with the same serial number in the two paths of a branch are paired off for joint use. A pair of time slots is only considered free if both slots are free; if one has been occupied, the pair is considered occupied. This proposition is essential for understanding the functioning of the network.

The branching unit transfers the information in an incoming time slot to all other branches. The serial number of the time slot, i.e. its position in time relative to the frame alignment signal, remains unaffected. For communication between two stations the serial number of the pair of time slots can therefore be used for addressing the blocks of information. This is termed time slot addressing. Thus an information block does not need to be preceded by an address block.

6 Stations

Each station is connected to both paths of a branch for receiving and transmitting messages (Figure 5).

A station receives messages by reading them as they pass by. All idle stations monitor both paths for calls.

A station with messages to send always uses both the time slots of a pair and consequently transmits over both paths, whereby an or-gate in each path adds the outgoing message to any message which may already be present in the time slot. Thus a station never has to delete an information block in a path. This feature assumes significance if optical fibers are used and a station is connected to both paths by way of passive optocouplers (Section 11).

7 Information Flow

For connection buildup the calling station searches for a pair of free time slots over which to transmit a busy code. The busy code propagates throughout the network as shown in Figure 6. By the end of the propagation time the occupation of the chosen pair of time slots will be known to all other stations. The call signal, which contains the address of the called station, is now transmitted. If the called station is free, it responds to the call signal by returning a free-state code over the same pair of time slots. The serial number of the pair of time slots thus serves as an address for the duration of the call (time slot addressing). The resulting information flow is shown in Figure 7:

(a) Between the calling and the called station one time slot of the pair of time slots serves for the go direction, while the other time slot in the second path serves for the return direction.

(b) Throughout the rest of the network the result of the combination of the messages from the two stations by the or-function will be transmitted over one of the two paths.

These or-operations take place only outside the connecting path between the two interconnected stations. In that part of the network the stations need only recognize the occupied state of the used pair of time slots. It is however necessary to assure that the or-operation will not simulate either a call to some station or a free time slot, for this would degrade the functioning of the network.

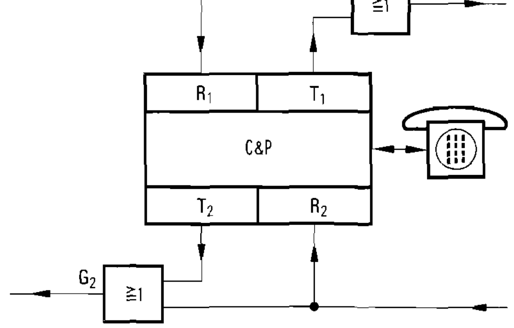

Figure 5 Connection of a station to both paths of a branch. R_1, R_2 Receive units, T_1, T_2 Transmit units, C & P Control and processing unit, G_1, G_2 or-gates

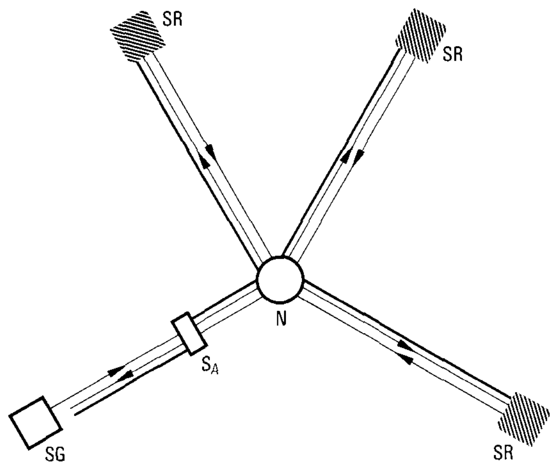

Figure 6 Information flow during transmission of busy code or a call signal by a calling station S_A. SG Synchronizing generator, SR Synchronizing reflex unit, N Node, —— Busy code or call signal

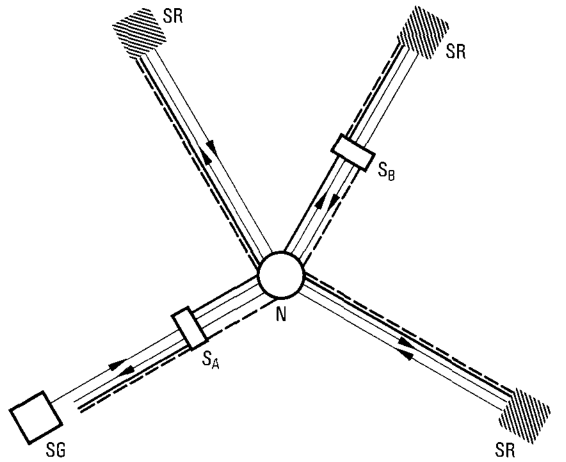

Figure 7 Information flow during two-way communication between two stations S_A and S_B SG Synchronizing generator SR Synchronizing reflex unit, N Node, —— Information from station S_A - - Information from station S_B —— Combination of information from stations S_A and S_B

8 Discussion of Possible Combinations

When the information in several time slots is combined by the or-function, the number of bits in the result which are set to 1 cannot be less than before the or-operation If exactly one occupied time slot is involved in an or-operation, its information will be reproduced If two or more occupied time slots are involved in an or-operation, the result will always be the simulation of an occupied time slot

Since stations transmit a call signal only over a pair of time slots which they have effectively occupied (Section 9), the combination of two call signals can never occur

When a call signal is combined with another signaling code by the or-function, the codes (010) and (001) give (011) Since the signaling bit is set to 0 but not all the remaining bits are set to 0, the time slot is considered occupied and its information is interpreted as signaling information Since however both specification bits are set to 1 the result is immediately recognizable as being due to an or-operation, so that the information in the time slot is invalid

If two other signaling codes are combined by the or-function, codes (001) and (001) will give (001), which usually leads to the simulation of another signaling code without the information in this time slot being recognizably the result of an or-operation The same applies if at least one time slot with usable information is involved in an or-operation The signaling bit will then always be set to 1, which simulates usable information without the information in that time slot being recognizably the result of an or-operation Since the results of these or-operations occur however only in branches and sections of branches which do not affect the two interconnected stations, they are without significance

Thus neither call signals nor pairs of free time slots will be simulated Usable information will moreover only be simulated if at least one time slot containing usable information was involved in the or-operation This means that all the conditions enumerated in Section 7 are satisfied

The method of encoding call signals, signaling codes and useable information outlined in Section 3 is only one of various solutions In order to prevent the simulation of call signals by transmission impairments it is practical to protect the bits that are used for differentiating the various types of information It is further conceivable that stations could be adapted so that they will not respond to a call signal or a signaling code unless it is received repeatedly

9 Example for Connection Buildup

When a subscriber lifts his handset to make a call he hears dial tone as a proceed-to-send signal Once he has keyed the complete call number of the wanted subscriber, a search proceeds for a pair of free time slots If none is available, the subscriber hears busy tone

Once a pair of free time slots has been found it will first be experimentally occupied for a certain interval Δt by the transmission of a busy code in both time slots If no busy code arrives over this pair of time slots during the interval Δt, it will be considered effectively occupied The interval Δt must be chosen at least twice as long as the maximum signal propagation time within the network

On rare occasions it may occur that two stations transmit the same busy code almost simultaneously for the experimental occupation of a pair of time slots hitherto recognized as free The combination of the busy codes by the or-function may then again result in a busy code If a busy code is received by a station over one of this pair of time slots during the experimental occupation of that pair, both slots will be instantly released This procedure prevents any pair of time slots from being occupied by more than one station

If call charges are metered (Section 12) by a central unit, the effective occupation of a pair of time slots will be followed by the transmission of the address of the calling station Since this takes place before the called station answers, the address will reach all points of the network without any danger of another address being simulated by an or-operation The calling station will then transmit the call signal containing the address of the called station All idle stations continuously monitor both paths and all time slots in order to determine whether they are being called When a free station recognizes that it is being called, it returns a free-state code over the pair of time slots, which triggers the bell or buzzer of the called station

If the called station is busy, no free-state code will be returned The non-arrival of the free-state code within a certain interval is interpreted by the calling station as called-station-busy The calling station now sends busy tone to the calling subscriber It is also possible for busy stations to monitor call signals and to return a called station busy code in response to any call signal that contains their address This feature will however not be gone into here

When a free-state code is received by a calling station, ringback tone is heard over the subscriber's handset

When the called subscriber lifts the handset, the called station stops ringing and transmits from then on coded samples of the message signal from the called subscriber instead of the free-state code The calling station therefore receives usable information over the time slot over which the free-state code had previously arrived This causes the removal of ringback tone and the switching through of the received samples to the subscriber The calling station now transmits the coded samples of the message signal from the calling subscriber in place of the call signal

Thus the called station receives usable information over the time slot over which the call signal had previously arrived This information is switched through to the called subscriber and both subscribers can now converse The flow of information between the two stations is now independent of which station originated the call (Figure 7)

As soon as one of the two subscribers cradles the handset, transmission stops at that end When the other station determines that the respective time slot is now free, the end-of-call tone is sent to the associated subscriber, transmission stops at that end too and thus the used pair of time slots is released No free-state code will however be returned in response to new call signals until the subscriber has cradled his handset

10 Network with Several Nodes

So far only a network with a single node has been considered The described concept can however also be applied to networks with more than one node (Figure 8) Frame coincidence between TDM signals at nodes

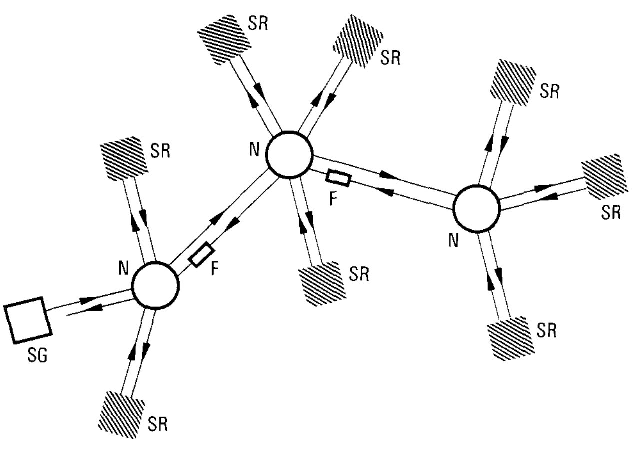

Figure 8 Network with several nodes (stations not shown) SG Synchronizing generator SR Synchronizing reflex unit N Node F (Frame) buffer

can however only be realized by interposing a delay element in each branch between two nodes The delay must be such that the round-trip propagation time between one node and the other is an integral multiple of the duration of the TDM frame A network with a total of i nodes will therefore need $i-1$ frame buffers, which will appreciably extend the signal propagation time This and the cost of frame buffers, which may be considerable, limits the number of nodes in this type of network

11 Application of Optical Fibers

The combination of two or more binary signals by the or-function can be represented as the ordinary addition of such signals followed by a threshold decision An optocoupler can be used for the addition of the signals The threshold decision follows automatically with the next signal processing step Thus a station can be connected to the two optical fibers by way of passive optocouplers, specifically a T-coupler in each path This offers the advantage of greater network reliability because fewer active devices are required in the transmission path Either a threshold device composed of active devices or a regenerative repeater must of course be connected at certain intervals in series with the transmission path on account of the attenuation and the finite bandwidth of the optical fibers

12 Call Charge Metering

Call charge metering requires no more than a knowledge of the addresses of the calling and the called station and of the instants at which conversation begins and ends At the subscriber network level it is practical for rate metering to be performed by a central unit Such a unit can be installed at any point within this network because all the required metering information is everywhere available It also monitors all the pairs of time slots The first address to arrive over a pair of previously free time slots will be that of the calling station The following call signal contains the address of the called station The start of the conversation is recognizable from the arrival of the first usable information block and the end from the arrival of the last usable information block It is practical to install the call charge metering unit at the end of one of the branches, such as that with the synchronizing generator All the information required for call charge metering can in that case be determined by monitoring only the path leading to that end of the branch

13 Concept Variants

In the described network an active station always transmits over two paths It is however alternatively possible to transmit only the call signal over the two paths and to use only the path leading to the other station for two-way connection.

In the described network a station uses an or-gate to combine the messages to be transmitted with any message that may be present in the chosen time slot. It is however alternatively possible to replace any message present in the chosen time slot by the message to be transmitted. A switch must in that case be interposed in the path instead of the or-gate. If however optical fibers are used the stations can in that case no longer be connected to the path by way of passive optocouplers alone.

At the node an outgoing time slot is now used to transmit the information from the incoming time slots of all the other branches after it has been combined by the or-function. A further alternative is to use a simple switch to switch one of these incoming time slots to the outgoing time slot. This incoming time slot may be chosen according to the occupancy of incoming time slots by means of a simple algorithm.

14 Conclusion

In so far as both operational and economic considerations do not disallow the use of networks featuring decentralized switching, they will be restricted to a subscriber-related network level of concentrators. Figure 9 shows an example of how the described TDM network could be realized for telephony.

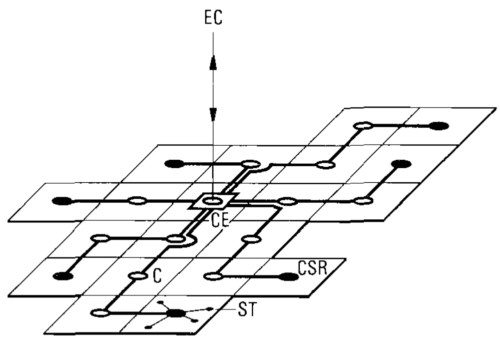

Figure 9 Example of a conceivable network configuration. ST Subscriber telephone, C Concentrator, CSR Concentrator with synchronizing reflex unit, CE Central equipment, EC External calls

The subscribers are connected over a radial network to a small exchange which will here be called a concentrator because of its location within the network. It should however be noted that besides concentrating the traffic such a concentrator also provides circuit switching for its own subscribers. Connections between any two subscribers on the same concentrator are built up by that concentrator alone. The concentrators represent the stations of the described type of branched TDM network. Connections between any two subscribers assigned to different concentrators are built up by the two concentrators involved and not by a switching center.

Assuming an ultimate capacity of 10 000 subscribers and normal traffic parameters, a bit rate of some 40 Mbit/s is required in both paths of the tree network. If optical fibers are used, a single multimode fiber per path will be sufficient.

The tree configuration used in the concentrator network level is divided into subnetworks with a limited number of subscribers, e.g. 1000, so as to obtain the same high degree of reliability as in present telephone networks. All subnetworks are connected to central equipment comprising a branching unit, a unit for disconnecting faulty subnetworks (wire breaks, synchronization failure), and other central units such as the synchronizing generator and the transfer units for external calls.

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